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Structure of Exotic Nuclei and Nuclear Forces

Gamow-Teller Strengths from (^{3}He,t) Charge-Exchange Reaction

Yoshitaka Fujita

Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

E-mail: fujita@rcnp.osaka-u.ac.jp

Abstract. Gamow-Teller (GT) transition is the most popular nuclear weak process with the nature of spin-isospin excitation. GT transitions in pf-shell nuclei, including those starting from unstable nuclei, are of interest, due to their importance in astrophysical processes. Weak processes, however, gives us rather limited information on the GT response of nuclei. We introduce high-resolution ($^3\mathrm{He}, t$) reaction at 0° and at an intermediate beam energy as a new spectroscopic tool for studying GT excitations. Owing to the high energy-resolution of the reaction ($\approx$ 30 keV), individual transitions can be observed up to the region of GT giant resonance. Assuming isospin symmetry for the $T_z = \pm 1 \rightarrow 0$ isobaric analogous transitions in isobars with mass number A, we present a new method to deduce GT transition strengths starting from proton rich exotic nuclei.

1. Introduction

A Gamow-Teller (GT) excitation represents a very basic spin-isospin ($\sigma\tau$) nuclear response. Interest in the accurate determination of "absolute" values and the distribution of Gamow-Teller transition strengths in pf-shell nuclei is increasing. These GT strengths are of importance in astrophysics at the core collapse stage of type II supernovae [1]. Direct information on the GT transition strength B(GT) can be derived from β-decay measurements. Pioneering studies were performed on several far-from-stability pf-shell nuclei (^{46}Cr, ^{50}Fe, ^{54}Ni, and ^{58}Zn) [2, 3, 4, 5]. In these studies, B(GT) values were derived for at most a few low-lying states with large ambiguities. Note that the study of the feeding to a higher excited state in β decay is difficult, because the phase-space factor (f-factor) decreases with the excitation energy.

The breakthrough came from charge-exchange (CE) reactions, like the (p, n) or $(^3\mathrm{He}, t)$ reactions. In particular, it was shown that measurements at scattering angles around 0° and at intermediate beam energies above 100 MeV/nucleon can map the GT strengths over a wider excitation energy. This is due to the fact that (a) GT states are dominant in the measured spectra, and (b) in most of the cases, there is a simple proportionality between the GT cross sections at 0° and the B(GT) values [6]

$$\frac{d\sigma_{\mathrm{CE}}}{d\Omega}(0^\circ) \;\simeq\; K\, N_{\sigma\tau}\, |J_{\sigma\tau}(0)|^2 B(\mathrm{GT}) = \hat{\sigma}_{\mathrm{GT}}(0^\circ) B(\mathrm{GT}), \tag{1}$$

where K and $N_{\sigma\tau}$ are kinematic and distortion factors, respectively, $J_{\sigma\tau}(0)$ is the volume integral of the effective interaction $V_{\sigma\tau}$ at momentum transfer $q = 0$, and $\hat{\sigma}^{\mathrm{GT}}(0^\circ)$ is the GT unit cross section at 0° for a specific mass A system. Therefore, the study of $B(\mathrm{GT})$ values can reliably be extended up to high excitations if a "standard $B(\mathrm{GT})$ value" from β decay is available.

Studies of GT strengths in pf-shell nuclei using (p, n) reactions at intermediate energies started in the 1980s. They provided rich information on the overall GT strength distributions [7], but individual transitions were only poorly studied due to their limited energy resolutions of $\approx$ 300 keV. Therefore, for pf-shell nuclei it was not easy to calibrate the unit cross section $\hat{\sigma}^{\mathrm{GT}}(0°)$ by using β-decay "standard $B(\mathrm{GT})$ values" [6]. In addition, the standard $B(\mathrm{GT})$ values, as mentioned, are poorly known for them.

A development in precise beam matching techniques [8] realized an energy resolution of $\approx$ 30 keV in intermediate energy $(^3\mathrm{He}, t)$ reactions at 0° [9]. With this one-order of magnitude better resolution, we can now study GT and Fermi states that were unresolved in the pioneering (p, n) reactions. The validity of the proportionality [Eq. (1)] was examined by comparing the GT transition strengths in the $(^3\mathrm{He}, t)$ spectra to the $B(\mathrm{GT})$ values from mirror β decays. Good proportionality was demonstrated for "$L = 0$" transitions with $B(\mathrm{GT}) \geq 0.04$ in studies of the $A = 26$ and 27 nuclear systems [11, 10]. By exploiting these properties, we present here a unique analysis to determine absolute $B(\mathrm{GT})$ values by combining the precise strength distribution from the $(^3\mathrm{He}, t)$ reaction with the decay Q-value and lifetime from the mirror β decay. The obtained spectra for $T_z = 1$ target nuclei ^{42}Ca, ^{46}Ti, ^{50}Cr, and ^{54}Fe are shown in Fig. 1. The method described here can be widely applied to these $T = 1$ and also to $T = 2$ systems.

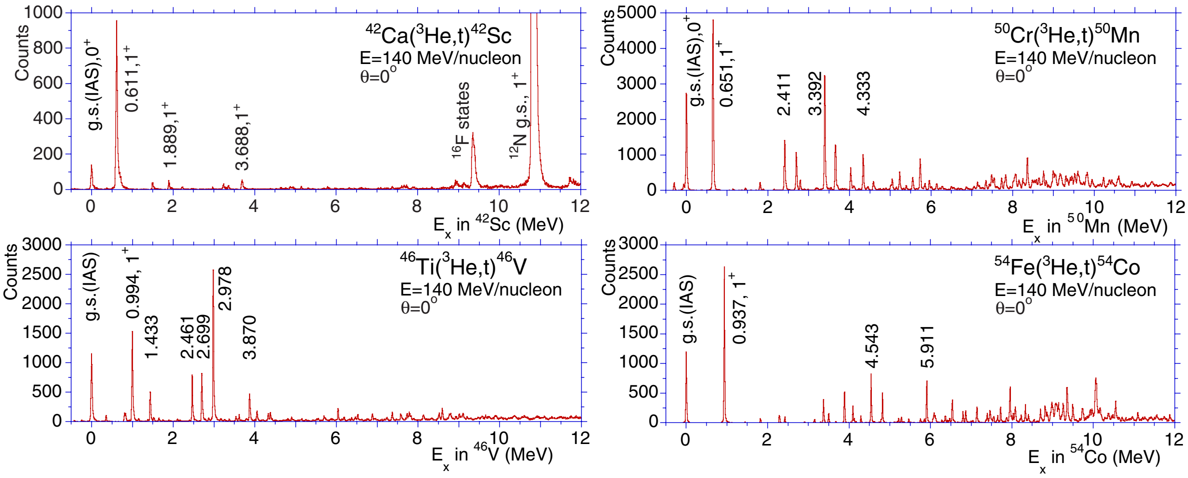

Figure 1. High-resolution $(^3\mathrm{He}, t)$ spectra for $T = 1$, pf-shell target nuclei at 0° and at an intermediate beam energy of 140 MeV/nucleon. Most of the prominent peaks are $L = 0$ GT states. The GT states are more fragmented as mass number A increases and more GT strengths are at higher excitation energies.

2. Isospin Symmetry GT Transitions

Under the assumption that isospin T is a good quantum number, an analogous structure is expected for nuclei with the same mass A but with different T_z (isobars). The corresponding states in isobars are called analog states, and are expected to have the same nuclear structure. Various transitions connecting corresponding analog states are also analogous and have corresponding strengths. In the "$T = 1$ triplet", GT and also Fermi transitions from the $J^\pi = 0^+$ ground states (g.s.) of the $T_z = \pm 1$ even-even nuclei to 1^+ states (GT states) and the 0^+ state in the $T_z = 0$ odd-odd nucleus between them are analogous, respectively (see Fig. 2). In the pf-shell region, $T_z = +1 \rightarrow 0$ transitions can be studied via $(^3\mathrm{He}, t)$ reactions on five stable $T_z = +1$ target nuclei, and analogous $T_z = -1 \rightarrow 0$ transitions can be studied via β decays. Assuming that the analogous GT transitions have the same $B(\mathrm{GT})$ values, the $B(\mathrm{GT})$ values from β decays [2, 3, 4, 5] can in principle be used as "standard B(GT) values". Then the study of B(GT) distributions can be extended by the (^{3}He, t) reactions to higher excitation energies overcoming the limits imposed by the Q-values in β decays. However, due to large uncertainties of β-decay B(GT) values, this idea was not practical.

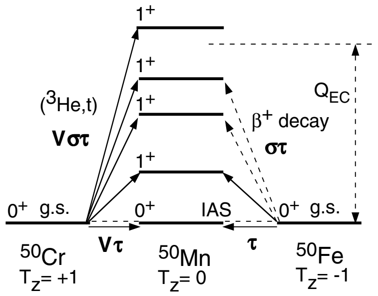

Figure 2. Schematic view of the isospin symmetry transitions from the $T_z = \pm 1$ nuclei to the $T_z = 0$ nucleus in the $A = 50$ isobar system. The Coulomb displacement energies are removed. The β decays to higher excited states are more suppressed by smaller phase-space factors f.

In a β decay, the partial half-life t_i of the ith GT transition and $t_{\rm F}$ of the Fermi transition multiplied by the f-factor are related, respectively, to the B(GT) and the reduced Fermi transition strength B(F),

$$ft_i = K/\lambda^2 B(\mathrm{GT}) \quad \text{and} \quad ft_{\rm F} = K/B(\mathrm{F})(1-\delta_c), \tag{2}$$

where $K = 6144.4 \pm 1.6$ [12], $\lambda = g_A/g_V = -1.266 \pm 0.004$ [13], and δ_c is the Coulomb correction factor. The Fermi strength is concentrated in the transition to the isobaric analog state of the g.s. of the mother nucleus (IAS), and has the value $|N - Z|$. Uncertainties in B(GT) values originate from uncertainties in the decay Q-value, the total half-life $T_{1/2}$, and the branching ratios (feeding ratios) determining t. The accurate determination of the feeding ratios to higher excited states is more difficult due to smaller f-factors. On the other hand, in the studies of analogous GT transitions using (^{3}He, t) reactions, relative transition strengths to these higher excited states can be obtained accurately from the $\sigma^{\rm GT}(0°)$ values. It should be noted that the β-decay feeding ratios can be deduced using these values and f-factors that are calculated from the decay Q-value. Absolute B(GT) values can then be deduced by further combining the total half-life $T_{1/2}$ of the β decay. Among the $T = 1$ triplets in the pf-shell region, these values are best known for the $A = 50$ system, i.e., for the ^{50}Fe $\rightarrow ^{50}$Mn β decay [$T_{1/2} = 0.155(11)$ s and $Q_{\rm EC} = 8.15(6)$ MeV]. However, so far the feeding was detected only to the first GT state at the excitation energy $E_x = 0.651$ MeV [3]. Therefore, a B(GT) value of 0.60(16) was deduced under the extreme assumption that there was no feeding to higher excited states [3].

3. Merged Analysis of β decay and (^{3}He, t) Measurements

Let us make this idea of B(GT) determination realistic. The inverse of $T_{1/2}$ is the sum of the inverse of the partial half-life $t_{\rm F}$ of the Fermi transition to the IAS and those of t_i's of GT transitions to the ith GT states

$$(1/T_{1/2}) = (1/t_{\rm F}) + \sum_{i=\mathrm{GT}} (1/t_i). \tag{3}$$

Applying Eq. (2), $t_{\rm F}$ and also t_i's can be eliminated,

$$(1/T_{1/2}) = (1/K)\left[B(\mathrm{F})(1-\delta_c)f_{\rm F} + \sum_{i=\mathrm{GT}} \lambda^2 B_i(\mathrm{GT}) f_i\right], \tag{4}$$

where $f_{\rm F}$ and f_i are the f-factors of the β decay to the IAS and to the ith GT state, respectively, and B_i(GT) is the B(GT) value of the transition to the ith GT state. In order to relate the strengths of GT and Fermi transitions in a CE reaction, we introduce the ratio R^2 of unit GT and Fermi cross sections at 0°

$$R^2 = \hat{\sigma}^{\mathrm{GT}}/\hat{\sigma}^{\mathrm{F}} = [\sigma_i^{\mathrm{GT}}/B_i(\mathrm{GT})]/[\sigma^{\mathrm{F}}/B(\mathrm{F})(1-\delta_c)]. \tag{5}$$

Owing to the isospin symmetry, this ratio R^2 is expected to be the same for the $T_z = \pm 1 \rightarrow 0$ transitions. Eliminating $B_i(\mathrm{GT})$ by using R^2, we get

$$\frac{1}{T_{1/2}} = \frac{B(\mathrm{F})(1-\delta_c)}{K\sigma^{\mathrm{F}}} \left[\sigma^{\mathrm{F}} f_{\mathrm{F}} + \frac{\lambda^2}{R^2} \sum_{i=\mathrm{GT}} \sigma_i^{\mathrm{GT}} f_i \right], \tag{6}$$

where $B(\mathrm{F}) = 2$ and $\delta_c = 0.0051(4)$ [12] can be used for the β decay of ^{50}Fe. Accurate (relative) cross sections of the IAS and GT states should be measured in the $T_z = +1 \rightarrow 0$, $^{50}\mathrm{Cr}(^3\mathrm{He}, t)^{50}\mathrm{Mn}$ reaction.

4. Experiment

The $(^3\mathrm{He}, t)$ experiment was performed at the high energy-resolution facility of RCNP, Osaka consisting of the beam line "WS course" [14] and the Grand Raiden spectrometer [15] using a 140 MeV/nucleon ^{3}He beam from the $K = 400$ Ring Cyclotron [16]. The outgoing tritons were momentum analyzed by the spectrometer placed at 0° and detected with a focal-plane detector system allowing for particle identification and track reconstruction [17]. A good resolution of scattering angle $\Delta\Theta \approx 5$ mrad was achieved by applying the *angular dispersion matching* technique [8] and the "overfocus mode" of the spectrometer [18]. The acceptance of the spectrometer was subdivided in scattering-angle regions in the analysis using the track information.

An energy resolution of $\Delta E = 29$ keV (FWHM) was realized by applying both the *dispersion matching* and the *focus matching* techniques [8, 19]. The "0° spectrum" for the events with $\Theta \leq 0.5°$ is shown in Fig. 3(a) up to $E_x = 6$ MeV. Well separated ^{50}Mn states were observed owing to the high energy resolution.

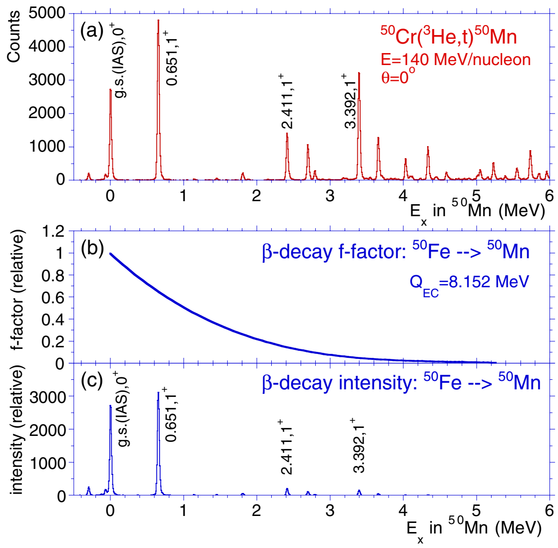

Figure 3. (a) The $^{50}\mathrm{Cr}(^3\mathrm{He}, t)^{50}\mathrm{Mn}$ spectrum for events with scattering angles $\Theta \leq 0.5°$. Major $L = 0$ states are indicated by their excitation energies in MeV. (b) The f-factor for the ^{50}Fe β decay, normalized to unity at $E_x = 0$ MeV. (c) The estimated ^{50}Fe β-decay energy spectrum that is obtained by multiplying the f-factor to the $^{50}\mathrm{Cr}(^3\mathrm{He}, t)$ spectrum. Note that the IAS is stronger by a factor of R^2/λ^2 in the real β-decay measurement (see text).

In order to distinguish GT states with "$L = 0$" nature, intensities of observed states were compared in the spectra for two angle cuts $\Theta = 0° - 0.5°$ and $1.5° - 2.0°$. All prominent states showed 0° peaked angular distributions, suggesting an $L = 0$ nature. Since the Fermi strength

Evaluated values [a]		$(^3\mathrm{He}, t)$ [b]		
E_x (MeV)	J^π	E_x (MeV)	L	B(GT)
0.0	0^+ [c]	0.0	0	
0.651	1^+	0.652	0	0.50(13)
0.800	2^+	0.800	≥ 1	
1.143	3^+	1.147	≥ 1	
1.802	3	1.805	≥ 1	
		2.411	0	0.15(4)
		2.694	0	0.11(3)
		2.790	0	0.03(1)
		3.177	≥ 1	
		3.392	0	0.35(9)
		3.654	0	0.14(4)
		4.028	0	0.07(2)
		4.333	0	0.11(3)

Table 1. States observed in the $^{50}\mathrm{Cr}(^3\mathrm{He}, t)^{50}\mathrm{Mn}$ reaction below $E_x = 4.6$ MeV. For the $L = 0$ states, B(GT) values are given.

[a] From Refs. [20, 21].
[b] Present work.
[c] The IAS with $T = 1$.

is concentrated in the transition to the IAS, it is very probable that these "$L = 0$" states are all GT states. Intensities of several weakly excited states increased at larger scattering angles, suggesting an "$L \geq 1$" nature (see Table 1).

The unit GT cross section in Eq. (1) gradually decreases as a function of excitation energy [6]. A distorted wave Born approximation (DWBA) calculation showed that the correction was small and about 4% at 4.6 MeV (for details see Refs. [22, 23]). In order to obtain an accurate Fermi cross-section (or intensity) of the transition to the g.s. IAS of ^{50}Mn, contributions from other manganese isotopes to the IAS peak were subtracted. The Fermi intensity inherent to the ^{50}Mn was estimated to be 92.0% of the observed IAS peak using the known abundances of chromium isotopes in the target.

5. GT transition Strengths in a Proton-rich Exotic Nucleus

Equation (6) shows that the inverse of $T_{1/2}$ is proportional to the sum of intensities of the observed Fermi and GT states weighted by f-factors, where a further correction factor λ^2/R^2 is needed for the GT intensities to compensate for the differences of coupling constants in the Fermi and GT β decays and unit Fermi and GT cross sections in the $(^3\mathrm{He}, t)$ reaction. The f-factors were calculated [24], and values normalized to unity at $E_x = 0$ are shown in Fig. 3(b). By assuming good isospin symmetry, the energy spectrum of GT transitions in the ^{50}Fe β decay can be estimated by multiplying the $^{50}\mathrm{Cr}(^3\mathrm{He}, t)$ spectrum with the f-factor [Fig. 3(c)].

This predicted β-decay spectrum shows that no significant strength is expected in the excitation energies higher than 4.6 MeV. Furthermore, it suggests that more than an order of magnitude better sensitivity was needed to detect the transitions to the second and higher excited GT states in the measurement of the ^{50}Fe β decay. The estimated feedings to these excited GT states amount in total to about 20% of the feeding to the first 0.651 MeV GT state, although each of them is small. By solving Eq. (6), we get a value $R^2 = 7.5 \pm 2.0$. The error mainly comes from the uncertainty in the $T_{1/2}$ value in the β decay measurement and also from the f-factor. The "absolute" B(GT) values calculated using Eq. (5) are listed in column 5 of Table 1. It should be noted that the excitation energy of 4.6 MeV analyzed presently is far above the reach of the ^{50}Fe β-decay study. Owing to the newly estimated feedings to higher excited GT states, the B(GT) value of the first GT state decreased by about 20% from the β-decay value of 0.60(16) to 0.50(13). Besides these statistical errors, there may be systematic errors due to wrong L assignment. We, however, consider this rather unlikely.

6. Summary and Prospects

We performed a ^{50}Cr(^{3}He$,t$)^{50}Mn experiment at an intermediate beam energy of 140 MeV/nucleon to study $T_z = +1 \rightarrow 0$ GT transitions. With an energy-resolution of 29 keV, discrete GT states were identified. The unknown "energy spectrum" of the $T_z = -1 \rightarrow 0$ ^{50}Fe β decay was estimated by multiplying the f-factor calculated from the Q-value of the decay. By further combining the half-life $T_{1/2}$, absolute values of GT transition strengths B(GT) were derived. Note that no feeding information, which is difficult to measure in a β decay, is used.

This "merged analysis" of determining absolute GT strengths by combining the complementary information from isospin mirror transitions can be extended to other $T = 1$ systems and also to $T = 2$ and even higher T systems, thus allowing to deduce the GT strength distributions in proton-rich exotic nuclei. Note that the development of new methods, like using various ion traps, is in progress for the accurate measurement of the $T_{1/2}$ and the Q values of these far-from-stability nuclei. The better knowledge on them will make this merged analysis even more fruitful as the means to determine the GT strengths, which are needed to deduce the astrophysical transition rates under extreme conditions.

The high-resolution (^{3}He$,t$) experiments were performed at RCNP, Osaka University. The author is grateful to the accelerator group of RCNP for their effort in providing a high-quality and stable ^{3}He beam. The present work was performed with the members of the high-resolution collaboration at RCNP. Some part of the work presented here has been published in Refs. [25, 26]. The author is grateful to the authors of these articles. This work was supported in part by Monbukagakusho, Japan under Grant No. 15540274.

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